

# Performance of Photosensors in the PandaX-I Experiment

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**ABSTRACT:** We report the long term performance of the photosensors, 143 one-inch R8520-406 and 37 three-inch R11410-MOD photomultipliers from Hamamatsu, in the first phase of the PandaX dual-phase xenon dark matter experiment. This is the first time that a significant number of R11410 photomultiplier tubes were operated in liquid xenon for an extended period, providing important guidance to the future large xenon-based dark matter experiments.

**KEYWORDS:** Dark Matter; Xenon; PandaX; Photomultiplier tubes; R11410; Random PMT rate; Afterpulsing .

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## 1. Introduction

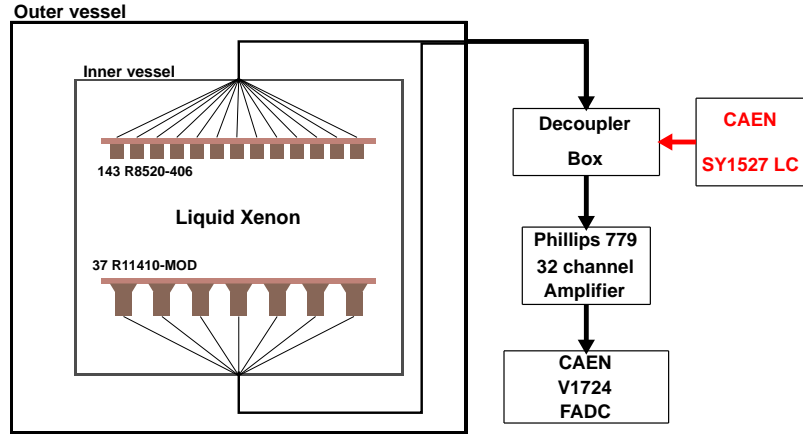
The PandaX project is a series of deep underground experiments aiming to study the properties of dark matter and neutrinos using xenon detectors in the China Jin-Ping Underground Laboratory [1]. The first phase of the experiment, PandaX-I [2], is a dual-phase xenon dark matter experiment using a time projection chamber (TPC), a technique similar to that used in earlier XENON10 [3], ZEPLIN-III [4], XENON100 [5], and LUX [6] experiments. The TPC contains an active target of  $\sim 120$  kg of liquid xenon. A stainless steel inner vessel is used as the liquid xenon cryostat, enclosed by a copper vacuum chamber acting as a vacuum jacket for the cryostat, a shield for the external gamma rays, as well as a radon barrier to the detector. The liquid xenon target is enclosed by a cylindrical TPC consisting of a field cage to drift the ionization electrons in the liquid and to create proportional scintillation in the gas for those electrons via electroluminescence. A top and bottom UV (178 nm) sensitive photomultiplier tube (PMT) arrays made up of 143 Hamamatsu R8520-406 one-inch 10-stage PMTs and 37 Hamamatsu R11410-MOD high quantum efficiency three-inch 12-stage PMTs, respectively, are looking into the target collecting photons from the prompt scintillation signals (S1) with a width of  $\sim 100$  ns and the delayed ionization signals (S2) with a width of  $\sim 2 \mu\text{s}$ . The detected light pattern on the PMTs as well as the time separation between the S1 and S2 allow reconstructions of the location of the energy deposition. The wall of the field cage is made out of polytetrafluoroethylene (PTFE) reflective panels to enhance the light collection.

PandaX-I started its liquid xenon operation in February 2014, and concluded data taking in October 2014, with an overall 80.1 live-day dark matter search data collected and published [7, 8].

Here we report the PMT performance during the entire data taking period. The remainder of this paper is organized as follows. In Sec. 2, we briefly describe the PMT assemblies, readout connections and signal processing. Then in Sec. 3 we discuss details of the PMT performance within the nine months of cryogenic operation, with some emphasis on the R11410-MOD tubes (bottom PMTs) since they are used for the first time with large quantities in a liquid-xenon-based experiment, followed by a short summary at the end.

## 2. PMT assemblies, connections, and signal processing

A diagram illustrating the connection between the PMT assemblies and the readout electronics is shown in Fig. 1. For each PMT, a positive high voltage (HV) divider circuit, customly built with



**Figure 1.** A diagram illustrating the connections between the PMTs and their readout electronics.

low radioactivity Cirlex PCB, was implemented with positive HV and signal combined on a single output miniature coaxial cable to minimize the number of cables in the cryostat. The design of the PMT bases was discussed in Ref. [2]. The voltage divider followed Hamamatsu’s recommended divider ratio. The overall base resistance was 12.5 and 18.5 M $\Omega$ , respectively, for R8520-406 and R11410-MOD. The back-termination resistor at the anode output was chosen to be 100 k $\Omega$  to increase the low frequency band width in order to avoid distortion of the S2 signals. To minimize radioactivity due to ceramic capacitors, we only kept one 10 nF capacitor between the last dynode and the anode, since the linearity was not a concern at the low energy dark matter signal region.

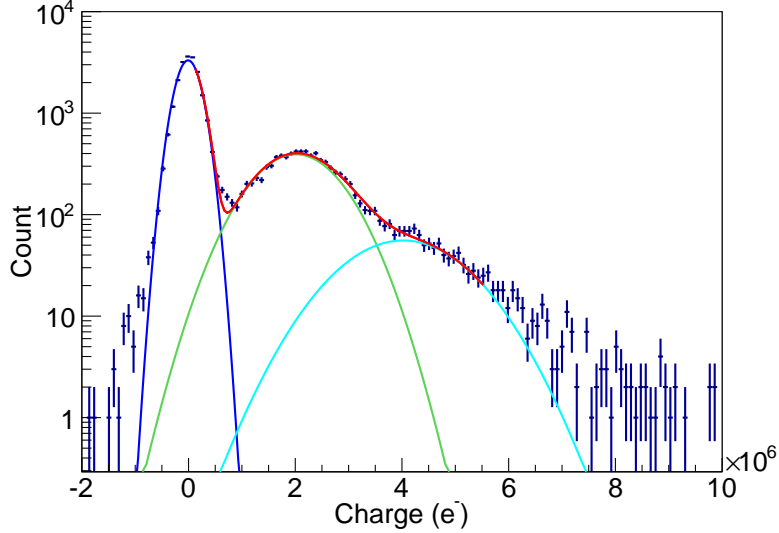
The cables for the top and bottom arrays were fed out through the feedthroughs located at the top and bottom of the inner vessel, respectively, then through a second feedthrough manifold located on the outer vessel to the electronics area. The HV and signal were decoupled using a three-stage RC decoupling circuit [2]. The value of the decoupling capacitor was chosen to be 100 nF in order to minimize the signal distortion for S2s. The PMT signals were amplified by the Phillips 779 linear amplifiers, then input into the CAEN V1724 digitizers to be read out by the data acquisition.

### 3. PMT performance

During the experiment, the PMTs were calibrated weekly using LEDs. Three LEDs (390 to 395 nm) outside the detectors were driven by a standard driver circuitry [9] to produce fast ( $\sim 10$  ns) and feeble light pulses, which were transmitted into the detector through three optical fibers and were further distributed by three Teflon diffuser rods mounted outside the PTFE panels. The driver also provided synchronized triggers for the data acquisition. The voltage of the driver was adjusted to ensure  $<20\%$  occupancies for every PMT in order to cleanly separate the single photoelectrons (SPEs). In addition, the gains, random PMT rates, as well as afterpulsing rates were monitored *in situ* during normal data taking. In this section, a few key properties of the PMTs shall be discussed in turn.

#### 3.1 Gain

The area of SPE waveform (in units of  $e$ ) was used to calibrate the gain of each PMT. A typical charge spectrum for a R11410-MOD PMT is shown in Figure 2. The measured PMT charge



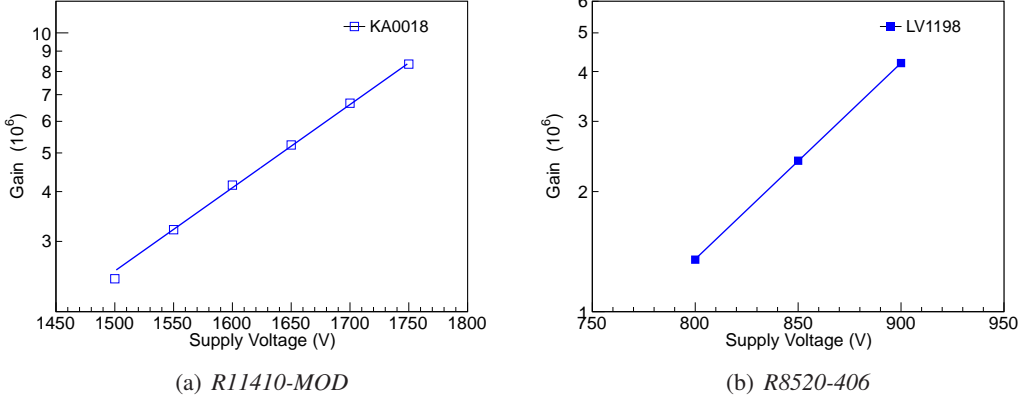
**Figure 2.** Low occupancy charge spectrum for a typical R11410-MOD PMT with a gain of  $\sim 2 \times 10^6$  during the LED calibration run in liquid xenon, and a combined fit of the pedestal (blue), SPE (green), and double PE (cyan) with the fit range indicated by the fit curve (red).

distribution  $f(q)$  is fitted with

$$f(q) = c_1 \times G(q, \mu_1, \sigma_1) + c_2 \times G(q, \mu_2 + \mu_1, \sqrt{\sigma_2^2 + \sigma_1^2}) + c_3 \times G(q, 2\mu_2 + \mu_1, \sqrt{2\sigma_2^2 + \sigma_1^2}), \quad (3.1)$$

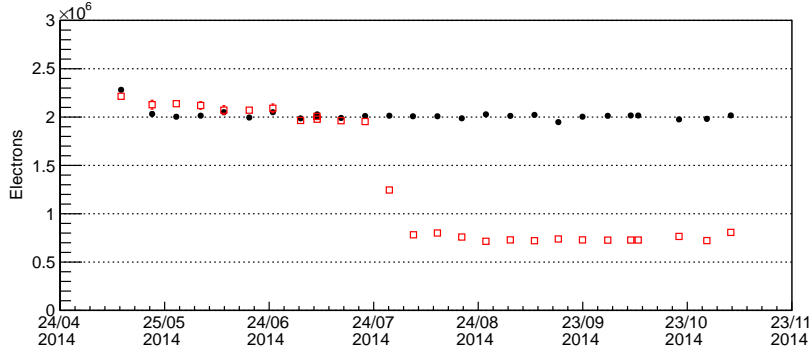
where  $G(x, \mu, \sigma) = e^{-(x-\mu)^2/2\sigma^2}$  is a standard Gaussian function. The first term describes the pedestal which comes from the electronic noise with a centroid and width of  $\mu_1 \sim 0$  and  $\sigma_1 \sim 0.3 \times 10^6$ , respectively. Similarly the second and third terms represent the single and double photoelectrons peaks, respectively, with their centroids and widths properly related. The SPE gain is typically  $\sim 2 \times 10^6$ . Typical gain values at different supply voltages for the two types of PMTs are

shown in Fig. 3, showing expected exponential relations. To operate under a uniform normal gain of  $2 \times 10^6$ , the supply voltage was set ranging from 1264 V to 1550 V (R11410-MOD) and 675 V to 881 V (R8520-406), respectively, for all the PMTs.



**Figure 3.** Gain vs. supply voltage for a typical R11410-MOD (a) and R8540-406 (b) PMT, showing an expected exponential relation with the supply voltage.

In Fig. 4, the stability of the gains of two R11410-MOD PMTs during six months stable data taking is shown. Most of the PMT gains are stable to  $<10\%$  except a few that we had to lower the supply voltage in order to avoid excessive random PMT rates (see Sec. 3.2).

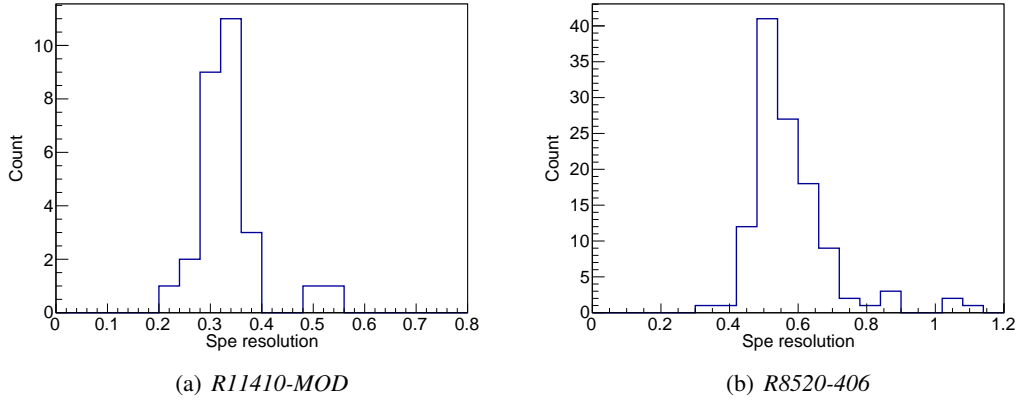


**Figure 4.** The gain history of two R11410-MOD tubes. Black dots are from a typical stable PMT. Red squares represent the gain of a PMT with the supplied voltage lowered twice during the run (from the 11<sup>th</sup> to 12<sup>th</sup>, and 12<sup>th</sup> to 13<sup>th</sup> points) to avoid excessive random PMT rates.

The resolution of a PMT to single photoelectrons was obtained from the LED calibration data. It is defined as  $\sigma_2/\mu_2$  based on Eqn. 3.1. For all the PMTs working stably under the normal gain, the SPE resolutions are summarized in Fig. 5. The average is 35% for R11410-MOD and 58% for R8520-406.

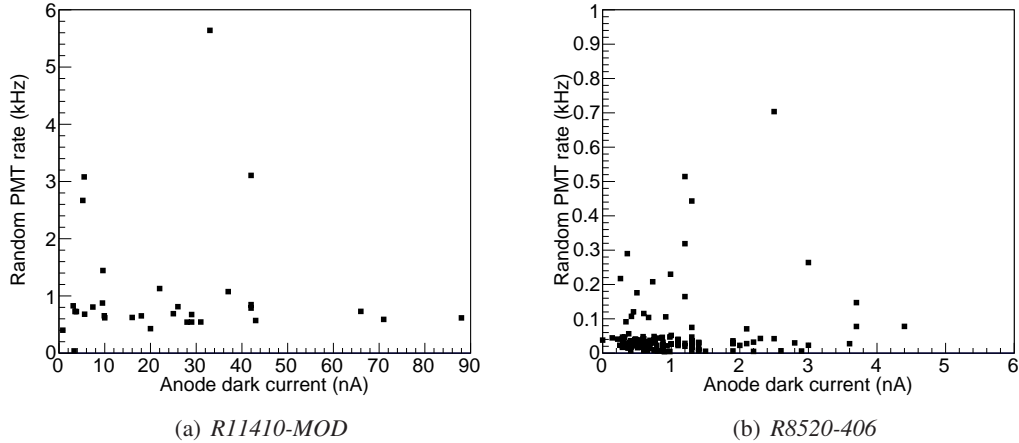
### 3.2 Random PMT rate

We define the random PMT rate as the rate of random SPE-like hits of each PMT independent of the physical event triggers. In the regular running of PandaX-I, each full data acquisition window is



**Figure 5.** SPE resolutions of all R11410-MOD (a) and R8520-406 (b) PMTs operated under normal gain obtained in a typical calibration run.

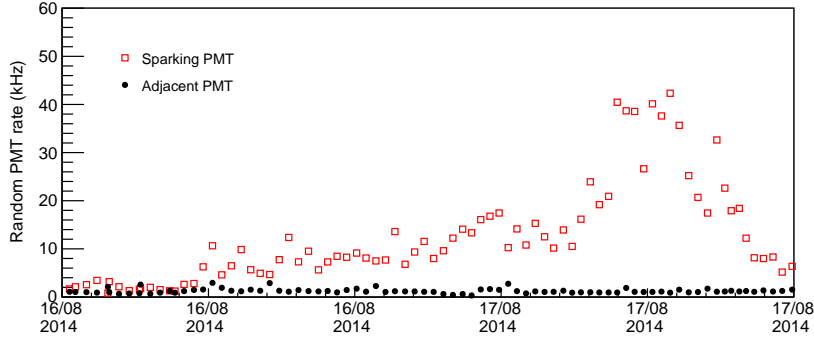
200  $\mu\text{s}$  with 100  $\mu\text{s}$  before the trigger. The maximum drift time in the 15 cm liquid xenon is 88  $\mu\text{s}$  (1.7 mm/ $\mu\text{s}$  drift velocity) [2]. We calculate the random PMT rate based on the number of SPE-like pulses in the first 5  $\mu\text{s}$  at the beginning of the waveform where no genuine S1 signal is expected. In Figs. 6(a) and 6(b), the average random PMT rates during the liquid xenon run vs. dark currents from the Hamamatsu data sheet are shown for R11410-MOD and R8520-406, respectively. On average, the random PMT rates were 1.07 kHz (R11410-MOD) and 0.06 kHz (R8520-406) during the operation in liquid xenon, whereas those measured in gaseous xenon under room temperature were 1.3 kHz and 0.3 kHz, respectively. In addition, no clear correlation between the random PMT rate and dark current was observed, indicating that the former might be dominated by additional light generation in the liquid xenon detector instead of the intrinsic thermionic electron emission and leakage current from the PMTs measured by the manufacturer.



**Figure 6.** Random PMT rate vs. anode dark current from Hamamatsu data sheets.

During the operation, the random PMT rates were not stable over time. Immediately after the xenon fill, the random PMT rate started from hundreds of kHz per PMT, but gradually decreased

to  $\sim$ kHz in a few days after the start of the liquid purification. We therefore suspect that the random PMT rate was correlated with the impurity level since photons from the discharging or S2 electroluminescence could liberate electrons from impurity atoms, generating additional photons inside the detector. During the stable data taking period, there were two typical types of rate excursions. The first type was that the rate increase was observed in an isolated PMT and no neighboring PMTs were affected, as illustrated in Fig. 7. Such a problem could sometime be cured by power-cycling the supply voltage of the affected PMT, indicating that the random PMT rate might be due to discharges inside the PMT, similar to that observed in Ref. [10]. This was a relatively minor issue as only limited number of channels were affected intermittently. The second

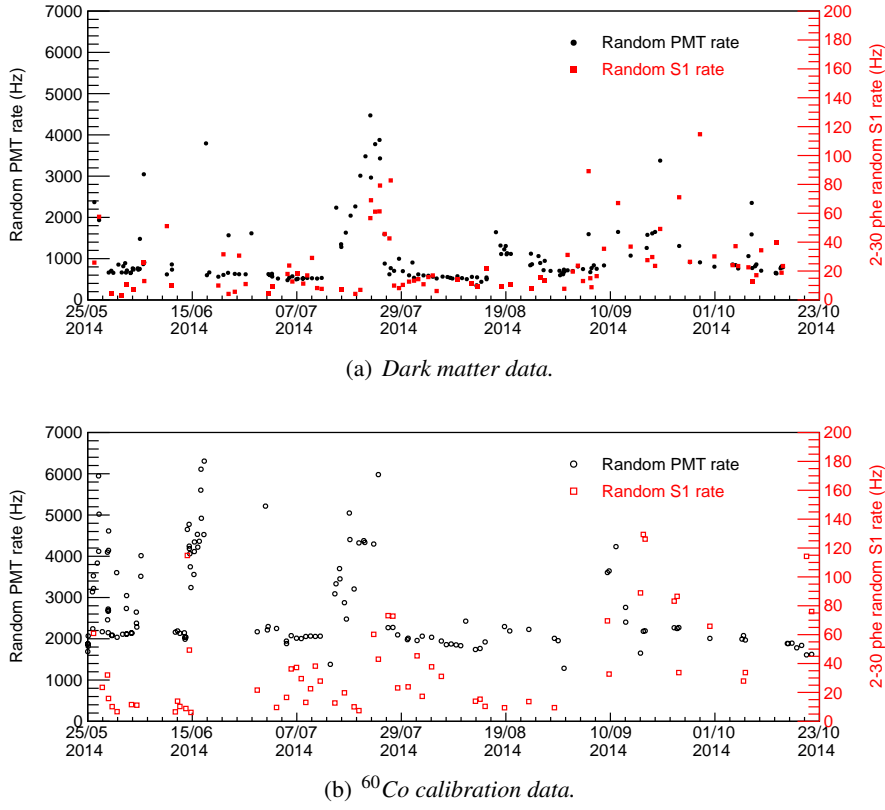


**Figure 7.** Random PMT rate evolution for two neighboring R11410-MOD PMTs; one (red open square) had a sudden increase but no change was observed in the other (black solid circle).

type of excursion affected PMTs more globally. As shown in Fig. 8, such excursions were also found to be correlated with the increase of the random S1-like rate, which differs from the random PMT rate by requiring a coincidence of at least three different PMTs. The excursion could have multiple origins. Spurious small discharges from the TPC electrodes could produce small light pulses affecting a cluster or all of the PMTs. In addition, if small amount of light was produced on a given PMT base, such light could leak into the sensitive region producing signals on a number of PMTs. Both hypotheses are supported by the fact that some times the instability could be cured by power cycling the HV for the electrodes and PMTs. One also observes in Fig. 8 that the average random PMT rate during the  $^{60}\text{Co}$  calibration run is significantly higher than that in the dark matter search run, confirming that the random PMT rates are not just intrinsic PMT properties but are also sensitive to the liquid xenon radiation environment. Given contributions from these additional photons generated from the detector, the mild decrease of random PMT rate at the liquid xenon temperature observed in R11410-MOD here is in contrast with the dark rate behaviors reported in other bench measurements where more significant decrease was observed [10, 11, 12].

### 3.3 Afterpulsing

Electrons emitted from the photocathode ionize the residual gas molecules trapped in the dynode structure. Positive ions drift to the PMT cathode under the electric field producing additional electrons when impinging onto the photocathode. This produces the so-called afterpulses after the primary photoelectron signals. The delayed time between the primary and afterpulse is approxi-



**Figure 8.** Average random PMT rate and the random S1 rate (indicated by legends) in 2 to 30 PE versus time in dark matter data (a) and  $^{60}\text{Co}$  calibration data (b). The vertical scale for the random S1 rates is labeled on the right.

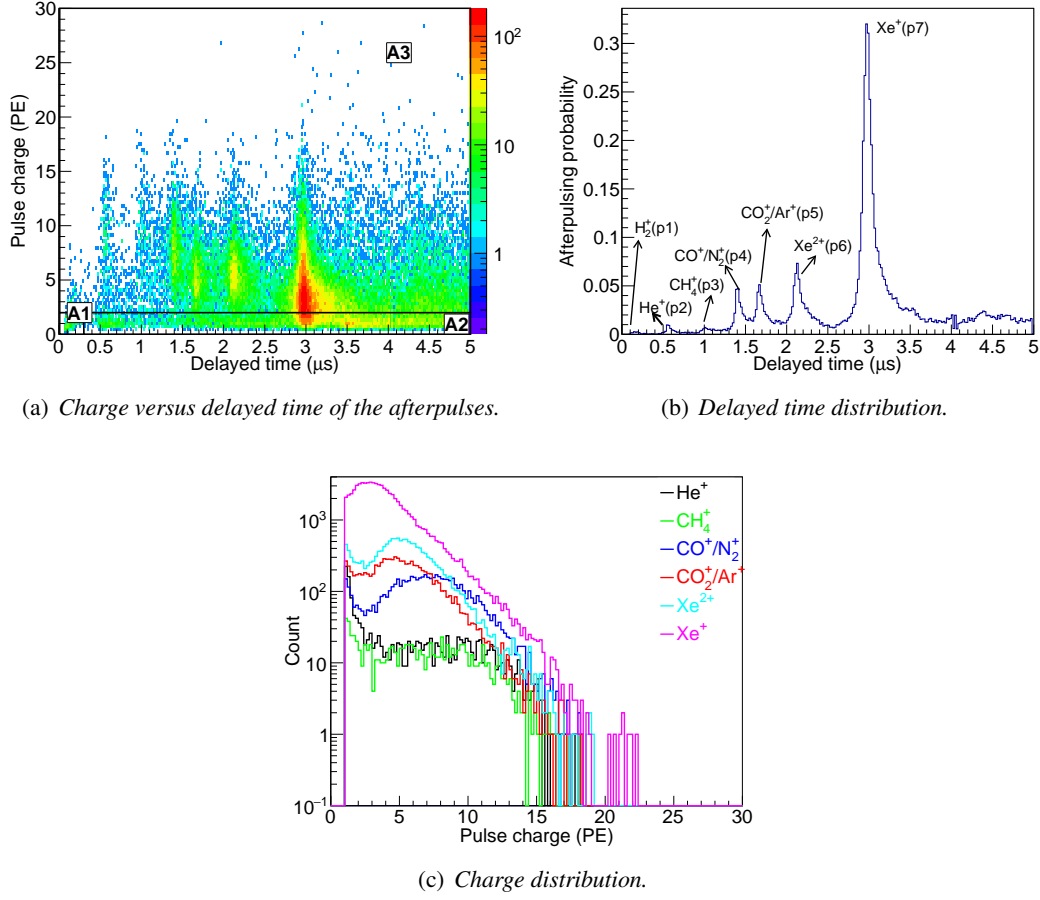
mately

$$\Delta t = \sqrt{\frac{2md}{qV}}, \quad (3.2)$$

in which  $d$  and  $V$  are the distance and voltage between the cathode and the first dynode where most of the residual gas molecules are expected, and  $m$  and  $q$  are the mass and charge of the ion, respectively.

Previous bench measurements of the afterpulsing for R11410 PMTs have been performed by number of groups [11, 12, 13]. In PandaX-I data, afterpulses were identified *in situ* during data taking by selecting pulses within  $5 \mu\text{s}$  after a small primary pulse with charge  $< 20$  PE. For each afterpulses, the delayed time and the charge of the afterpulse was recorded. For illustration, the two-dimensional distributions of delayed time vs. charge as well as the respective one-dimensional projections are shown in Fig. 9 for a R11410-MOD PMT with relatively high afterpulsing rate. Using the same classification as in Ref. [12], Fig. 9(a) was separated into three regions as indicated. A1 represents small pulses ( $\leq 2$  PE) happened within  $0.3 \mu\text{s}$  after the primary hit. The delay is mostly caused by elastic scattering of secondary electrons on the first dynode [14]. A2 represents random hits ( $\leq 2$  PE) between  $0.3$  to  $5 \mu\text{s}$  after the primary hit. A3 contains the afterpulses ( $> 2$  PE) caused by the residual gas ions. Peaks due to different ions can be clearly identified from the





**Figure 9.** Distributions of the afterpulses for a R11410-MOD PMT with high afterpulsing rate: (a) charge vs. delayed time, each point representing an afterpulse identified after the primary pulses  $< 20\text{PE}$ ; (b) the delayed time distribution of the afterpulses in the A3 region with individual ionic components indicated; and (c) charge distribution of the afterpulses associated with different ionic components (see legend).

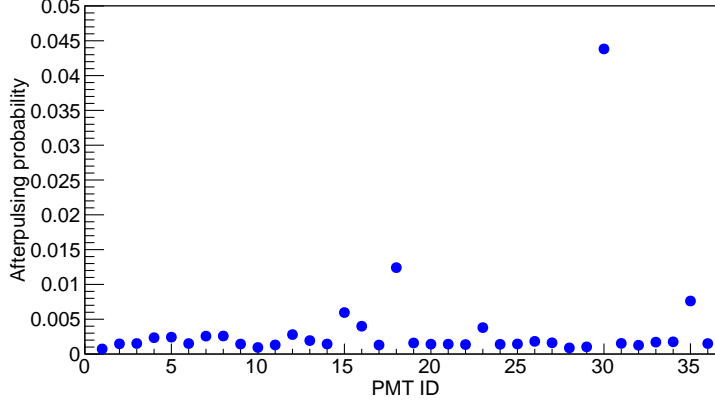
timing distribution in Fig. 9(b), similar to those in Refs. [11, 12, 13]. Peak located at around  $3\ \mu\text{s}$  is identified as the  $\text{Xe}^+$  peak, and similarly all other peaks are identified using Eqn. 3.2. The charge distributions of the afterpulses for individual ionic peaks in Fig. 9(b) are shown in Fig. 9(c). For all  $+1$  charged ions, one finds qualitatively that the average charge of the afterpulses grows with the decrease of the mass of the ion, as expected from their increasing ionization capability.

The probability of occurrence of afterpulses per single PE (APP) in a given data run is

$$APP = \frac{\sum N_{\text{afterpulse}}}{\sum Q_{\text{primary}}}, \quad (3.3)$$

where  $\sum N_{\text{afterpulse}}$  is the total number of identified afterpulses and  $\sum Q_{\text{primary}}$  is the summation of the charge of the primary in the unit of PE. Since the primaries were selected to be  $< 20\text{PE}$ , pile-up of afterpulsing per primary is negligible, and the APP in Eqn. 3.3 was verified to be insensitive to the cut to the primary charge. In Fig. 10, the APP in A3 (Fig. 9(a)) for all active R11410-MOD PMTs are summarized. One sees that the APPs for most of the PMTs are less than 1%, except a

few which are at a few percent level. The average APP for the R11410-MOD PMTs is 1.7%, with details listed in Tabel 1. We observe no correlation between the APP and the measured random PMT rate. The average APP for the R8520-406 tubes is less than 0.3%.



**Figure 10.** Measured APPs for individual active R11410-MOD PMTs.

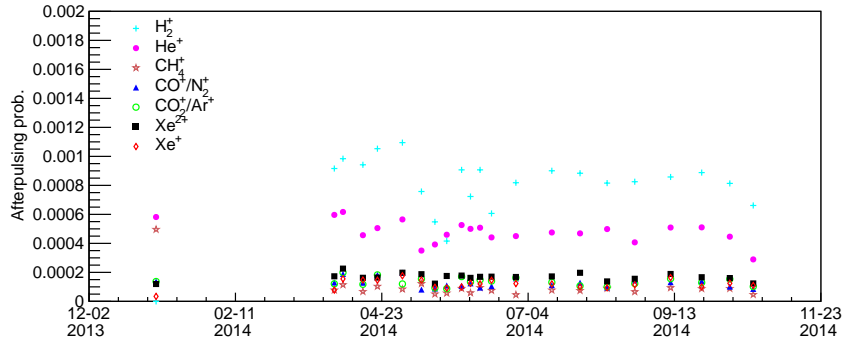
PMT	Total (%)	A1	A2	A3	p1	p2	p3	p4	p5	p6	p7
AVE	1.70	0.38	1.13	0.19	0.05	0.03	0.01	0.02	0.03	0.02	0.02
ZK6307	4.34	0.67	2.43	1.24	0.11	0.06	0.01	0.04	0.24	0.14	0.65
ZK6313	8.97	0.03	4.56	4.38	0.01	0.05	0.04	0.28	0.37	0.64	2.99
KA0019	2.49	0.44	1.30	0.76	0.06	0.03	0.01	0.01	0.11	0.11	0.44

**Table 1.** Summary of average R11410-MOD PMT APPs as well as those for the abnormal ones. The entries p1 to p7 in the table refer to the APPs for  $H_2^+$ ,  $He^+$ ,  $CH_4^+$ ,  $CO^+/N_2^+$ ,  $CO_2^+/Ar^+$ ,  $Xe^{2+}$ , and  $Xe^+$  peaks, respectively.

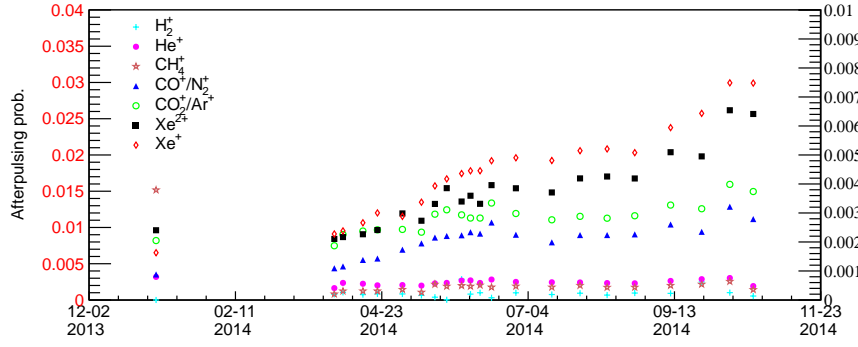
The evolution of the APPs from two PMTs, one typical, the other one abnormal, is shown in Fig. 11. The typical one is rather stable over time. For the abnormal PMT, the APP of all ionic components started to increase from the beginning of the liquid xenon run, strongly indicating a leak related effect.

### 3.4 Saturation for large pulses

As mentioned in Sec. 2, to reduce the radioactivity level from the ceramic capacitors, we only kept one capacitor between the last dynode and the anode. This was not a problem for the low energy signals in the dark matter search region, but the linearity of the PMT for large pulses, S2 pulses in particular, was affected. On the other hand, if the supply voltage was reduced, the linearity could be recovered to a certain extent. To demonstrate this, in Fig. 12 the measured S2 charge vs. S1 charge are shown for two different PMT high voltage settings. One sees that under the normal HV setting, the measured S2 starts to exhibit saturation for S1 above  $\sim 600$  PE which is approximately 194 keV<sub>ee</sub> electron-equivalent energy.

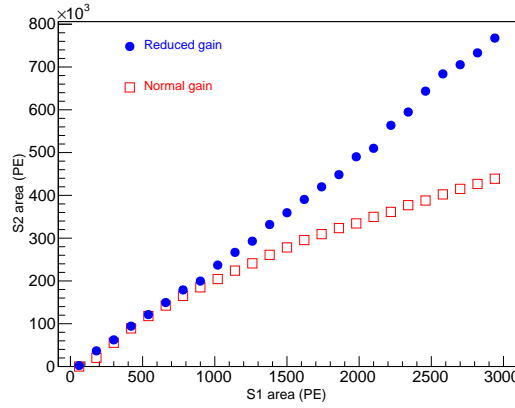


(a) A typical PMT.



(b) PMT with abnormal APP.

**Figure 11.** APP vs. time for two R11410-MOD PMTs, one typical (a) and one abnormal (b). The very first data point in each figure is obtained in the gas xenon run under room temperature. Note that in (b) the scale for  $\text{Xe}^+$  is indicated on the left side and the others on the right.



**Figure 12.** The mean S2 vs. S1 in PE when all PMTs were operated at the normal gain of  $2 \times 10^6$  (red) and reduced gain of  $5 \times 10^5$  (blue). Saturation of S2 signals was observed in the normal gain data for high energy events. The reduced gain data showed improved linearity for larger S2, but had a slight “overshoot” for S1 around 200 PE due to a higher trigger threshold for S2, as well as a lower signal finding efficiency for S1.

### 3.5 Other performance issues

During the PandaX-I operation, one bottom PMT was fully disabled due to unstable random PMT rate. We suspect that intermittent discharging happened on the PMT base assembly (Sec. 3.2). In addition, four bottom and eight top PMT channels gradually developed connection problems, resulting in improper base resistance, capacitance, or frequent HV trips, and were disconnected. To avoid complication due to a time-dependent light yield, in the full exposure analysis we inhibited all these 13 PMTs. This, and the updated baseline calculation algorithm [8], are the two major factors contributing to the decrease of average light yield for S1 from 7.3 PE/keV<sub>ee</sub> (standard zero electric field value at 122 keV<sub>ee</sub>) in the first 17.4-day data period [7] to 6.0 PE/keV<sub>ee</sub> in the full exposure data [8]. Since the bottom PMTs dominated the light collection for S1, and the photon distribution was measured to be rather uniform independent of the interaction vertex, this represents a constant downward correction to the photon detection efficiency. Using a dedicated Monte Carlo including the photon propagation in the TPC, the effects due to disabled top PMTs to the position reconstruction were studied and verified to be minor. To set the scale, at the 300 PE S2 event selection threshold [8], for events located at the center of a disabled PMT, reconstructed position resolution changed from about 5 mm to less than 7 mm, leading to a negligible influence to the fiducial volume selection.

## 4. Summary

We report the long term performance of 180 PMTs in the PandaX-I experiment operated for nine months in a liquid xenon environment. Details of key PMT parameters such as the gains, SPE resolutions, random PMT rates, and afterpulsing probabilities are presented. The unstable random PMT rate was the most important issue identified during the run. The problem appeared to be related to the discharges either inside the PMT, causing excessive random PMT rates in isolated PMTs, or from the base assemblies and/or the TPC electrodes, affecting a cluster or all PMTs. This study provides an important guidance to the design of the PandaX-II experiment, as well as future xenon-based dark matter experiments using R11410 series as the primary photon sensors.

## 5. Acknowledgement

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